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Tuning the Clock: Uranium and Thorium Chronometers Applied to CS 31082-001

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Abstract. We obtain age estimates for the progenitor(s) of the extremely metal-poor ([Fe/H = −2.9) halo star CS 31082-001, based on the recently reported first observation of a Uranium abundance in this (or any other) star. Age estimates are derived by application of the classical r-process model with updated nuclear physics inputs. The [U/Th] ratio yields an age of 13±4 Gyr or 8±4 Gyr, based on the use of the ETFSI-Q or the new HFBCS-1 nuclear mass models, respectively. Implications for Thorium chronometers are discussed.

1. Introduction

Abundance measurements of long-lived radioactive neutron-capture species found in r-process-enhanced extremely metal-poor (EMP) stars offer the opportunity to determine the age of the progenitor object(s) that contributed these elements into the presently observed stellar material, by comparison with r-process model predictions (Cowan et al. 1999; Meyer & Truran 2000). Such age estimates do not rely on assumptions about Galactic chemical evolution, yet provide constraints on the nature of r-process nucleosynthesis, and limits on the age of the Galaxy and the universe.

So far this method has been applied to Thorium observations in several EMP stars. For the first time, Uranium now has also been detected, in the EMP halo star CS 31082-001 ([Fe/H] = –2.9) (Cayrel et al. 2001; also this volume). Instead of one chronometer – the previously used [Th/X] abundance ratio (with X representing a reliably observed stable r-process element such as Eu) – there are now three principal chronometer pairs available, [Th/X], [U/X], and [U/Th]. These chronometer pairs can be combined to obtain a more reliable age estimate (see Goriely & Clerbaux 1999). In that way one can also place another constraint on r-process model parameters by demanding consistency of the different inferred ages. R-process model parameters determined in this way for CS 31082-001 could then be used for more reliable age determinations of other stars, even those for which no U can be detected.

2. Calculations

We calculated the r-process production of ^{238}U and ^{232}Th using the classical site-independent model (Cowan et al. 1999) assuming (n,γ)-(γ,n) equilibrium (waiting-point approximation) and an iron seed. R-process abundances are obtained from a superposition of abundance distributions where weights and timescales obey a power law over the neutron density. Assuming that the abundance pattern in CS 31082-001 resembles a solar r-process pattern (see Fig. 1), the four free parameters of the model are determined by fitting the calculated abundances to the solar system r-process abundances (Arlandini et al. 1999) at the $124<A<133$ and $189<A<199$ abundance peaks, as well as at Pb. Because Pb is a product of α-decay chains like Th and U, it provides an important constraint for the U and Th production estimates (Pb has not yet been detected in CS 31082-001, Hill et al., this volume).

The necessary nuclear physics input for our calculations are masses, β-decay half-lives, branchings for β-delayed neutron emission, and the rates of fission processes for very neutron-rich nuclei. While we used experimental data where available, the vast majority of the required nuclear information needs to be predicted by theory. For comparison, calculations were performed with two nuclear mass models, the frequently used ETFSI-Q (Pearson, Nayak & Goriely 1996), and the recently developed HFBCS-1 (Tondeur, Goriely & Pearson 2000), which we use here for the first time in a r-process calculation. The β-decay data were the same as in Cowan et al. (1999). It has been emphasized before that the proper treatment of fission processes is crucial for calculating the r-process yields of Thorium and Uranium (e.g., Cowan, Thielemann & Truran 1991; Goriely & Clerbaux 1999). In this work we re-calculated neutron-induced fission, β-delayed fission, and spontaneous fission rates based on the new fission barriers from Mamdouh et al. (1998), using the methods outlined in Kodoma & Takahashi (1975).

Ages were determined based on the predicted abundance ratios [U/Th], [U/X], and [Th/X]. To compensate for the deficiencies in the abundance predictions of stable r-process elements, and to reduce the impact of observational errors in the [U/X] and [Th/X] ratios, we also fitted both the observed and the simulated elemental abundance pattern to the solar one. Then the ratios [U*f/U0] and [Th*f/Th0] alone can be used for an age determination. (U* = observed stellar abundance, U0 = predicted abundance, f = normalization factor).

We conducted an extensive investigation of the influence of uncertainties on the age determination. (1) β-decay rates: To obtain a conservative estimate of the possible influence of errors in the β-decay data, we randomly changed the β-decay half lives by factors between 0.2 and 5. Branchings for β-delayed neutron emission were also varied. One hundred calculations were then made to determine the variance of the r-process abundance predictions (Δ_β). (2) Model uncertainties: We determined the range of the four r-process model parameters that still result in a reasonable fit of the solar abundance pattern. This parameter range leads to an uncertainty $\Delta_{\rm par}$ in the predicted abundances. While this error is small for [U/Th], it turns out to be unacceptably large for the [U/X] and [Th/X] ages. However, in this work we constrain the simulation parameters by requiring best possible consistency with the [U/Th] age. This constraint leads to the same small $\Delta_{\rm par}$ for all abundance ratios. (3) Observational errors: These lead to uncertainties in the derived abundance ratios $\Delta_{\rm exp}$. (4) Mass models: We determined the simulation parameters individually for the two mass models ETFSI-Q and HFBCS-1. Generally there is good agreement in the abundance predictions between the two calculations in the critical 230<A<260 mass region. Yet, the pronounced drop in the calculated abundances in the mass region 229<A<238 before β-decay occurs 5 mass units earlier for the ETFSI-Q model, resulting in a somewhat lower Th abundance and a higher age estimate. This is probably a consequence of a difference in the prediction of the onset of deformation in the ^{244}Tl region. (5) Fit to abundance pattern: The scaling factor f for the [U*f/U0] and [Th*f/Th0] age estimates has an error $\Delta_{\rm logfac}$, originating from the discrepancies between the calculated and the observed abundance patterns for stable r-process elements (see Fig. 1).

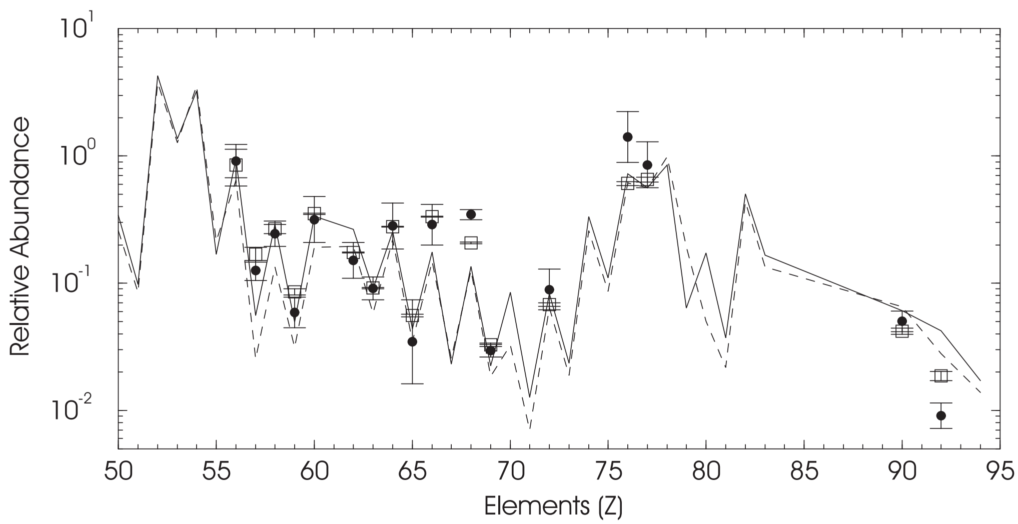

Figure 1. Calculated r-process elemental abundances for the ETFSI-Q mass model (solid) and the HFBCS-1 mass model (dashed) compared to the normalized solar abundances (open squares) and the observed abundances in CS 31082-001 (filled dots).

3. Results

Fig. 1 shows our calculated r-process elemental abundances. In Tab. 1 we list our resulting age estimates together with the various sources of uncertainties.

Table 1. Age estimates and errors. Log(ϵ_0) is the predicted abundance ratio produced in the r-process. Δ's refer to errors in the predicted abundance ratios (see text).

Ratio	Model	Log(ϵ_0)	Δ_β	$\Delta_{\rm par}$	$\Delta_{\rm exp}$	$\Delta_{\rm logfak}$	$\Delta_{\rm total}$	Age (Gy)
U/Th	ETFSIQ	-0.16	0.07	0.04	0.16		0.18	12.6±3.9
U/Th	HFBCS1	-0.37	0.08	0.04	0.16		0.18	8.2±4.0
U*f/U0	ETFSIQ	-0.95	0.09	0.04	0.14	0.1	0.20	10.5±2.9
U*f/U0	HFBCS1	-1.12	0.09	0.04	0.14	0.1	0.20	7.9±2.9
Th*f/Th0	ETFSIQ	-0.79	0.09	0.04	0.08	0.1	0.16	5.9±7.5
Th*f/Th0	HFBCS1	-0.76	0.08	0.04	0.08	0.1	0.16	7.2±7.3
U/Gd	ETFSIQ	-0.78	0.10	0.04	0.23		0.25	10.5±3.7
U/Gd	HFBCS1	-0.90	0.11	0.04	0.23		0.26	8.8±3.8
Th/Gd	ETFSIQ	-0.62	0.10	0.04	0.20		0.22	6.1±10
Th/Gd	HFBCS1	-0.53	0.11	0.04	0.20		0.23	10.2±11
Th/Ir	ETFSIQ	-0.96	0.11	0.04	0.20		0.23	12.6±11
Th/Ir	HFBCS1	-0.94	0.11	0.04	0.20		0.23	13.7±11

The most robustly predicted abundance ratio is [U/Th], which represents therefore the most reliable chronometer. Yet, the mass-model dependence is still substantial, yielding ages of 13±4 Gyr (ETFSI-Q) or 8±4 Gyr (HFBCS-1). β delayed fission leads to significant corrections when adopting the new Mamdouh et al. fission barriers (+0.9 Gyr for the [U/Th] age, –0.8 Gyr for the [U/X] ages and 4 Gyr (!) for the [Th/X] ages). While more theoretical work is needed, this indicates that β delayed fission should not be neglected. While some of the predicted [U/X] and [Th/X] ages agree well with [U/Th], others show discrepancies. The [U*f/U0] and [Th*f/Th0] ages average over these discrepancies, and at least [U*f/U0] provides a reasonable age estimate as well ([Th/X] suffer from large observational uncertainties in the present data). However, we are now in the position to pick the [U/X] and [Th/X] estimates that agree best with the [U/Th] age. These are the ratios based on Gd and Ir abundances (Hill et al., this volume). Our predicted ratios for [Th/Gd] and [Th/Ir] can therefore be used for improved age estimates of stars where no Uranium can be detected. In principle, other observed [Th/X] ratios could be used together with our calculations, if an appropriate correction factor would be applied. Such a correction factor can now be determined by requiring consistency with [Th/Ir] and [Th/Gd]. However, it will be crucial to verify whether the consistency of the age estimates based on [U/Th], [U/Gd], and [U/Ir], as obtained from our r-process model, holds for a larger sample of EMP stars.

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